International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 7, Issue 4, pp 149-155, April-2023

https://doi.org/10.47001/IRJIET/2023.704024

Dynamic Wireless Charging System for Electrical Vehicles

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***Abstract* - Electric vehicles are seen as an alternative option given the scarcity of resources. In order to increase the usage of EVs in daily life, convenient and reliable methods of charging EV batteries are very important, so Wireless Power Transfer (WPT) is being considered as a solution to charge the batteries. In this project, prototype hardware for charging system with dual coils and operating frequency of 60 kHz will be designed and implemented. Plug-in electric vehicles (PEVs) are overwhelmed by the need for plug-in cables and chargers, the galvanic isolation of the onboard electronics, the bulk and cost of this charger, and the large assemblies of energy storage systems (ESS) required. But through the use of wireless charging systems, wireless charging capability offers customer convenience, inherent electrical isolation, grid-side regulation, and reduces the size of onboard ESS through on-road dynamic charging. The main goal of our project is to design and develop a vehicle-grade antenna system that uses resonant magnetically-coupled wireless energy transfer technology to EV charging system. The use of WPT in electric vehicles enables clean, comfortable and safe operation. At the heart of WPT systems are primary and secondary coils. These coils form a weakly coupled system where the coupling coefficient is between 0.1 and 0.5. To transmit the rated power, both sides must be tuned by resonance capacitors. The operating frequency is a central selection criterion for all applications and particularly influences the dimensioning of the coils and the selection of the components for the power electronic circuit. A resonant wireless transmission system is designed for vehicle charging technology.**

Keywords: WPT, wireless power transfer, EVs, electric vehicles, wireless charging.

I. INTRODUCTION

Non-contact electromagnetic induction power transmission uses the phenomenon that applying an electric current to one of the adjacent coils induces an electromotive force in the other coil with magnetic flux as a medium. Wireless Power Transfer (WPT) is an innovative technology that powers communication devices without a power adapter [1].

With the remarkable advances that have been made in recent times, this technology has attracted a lot of attention from scientists and R&D companies around the world. Recently, mobile devices such as mobile phones, laptops, tablets and other portable devices equipped with rechargeable batteries have become widespread. It is a well established concept that, for propagation of a electromagnetic wave electromagnetic energy lies behind it. In theory, we can use all electromagnetic waves for wireless power transmission (WPT).

The only difference between a wireless communication and wireless power system is efficiency. Maxwell's equations show that the electromagnetic field and its strength scatter in all directions [2]. Although we transmit energy in a communication system, the transmitted energy spreads in all directions. Although the power received is sufficient for information transmission, the efficiency from the transmitter to the receiver is quite low and hence it’s not called as a WPT system.

Electric vehicles differ from fossil-fuel vehicles in that the electricity they use can be generated from a variety of sources, including fossil fuels, nuclear power, and renewable sources such as tidal power, solar power, and wind power, or any combination of these sources are utilized [3]. And finally the energy generated is transferred to electrical vehicles via a wireless inductive coupling for wireless charging or through a direct electrical cable connection.

The electricity can then be stored on board the vehicle via a battery, a flywheel or super-capacitors [4]. Typically, vehicles with engines that operate on the combustion principle can obtain their energy from only one or a few sources, mostly non-renewable fossil fuels. A key advantage of electric or hybrid electric vehicles is regenerative braking and suspension, their ability to recover energy normally lost during braking in the form of electricity that is fed back into the on-board battery. However, they are highly dependent on external energy support [5].

1.1 Resonance inductive coupling

Resonance is natural phenomenon which occurs usually in many different forms of the nature. In general, resonance involves energy oscillating between two modes, a well-known example being a mechanical pendulum in which energy oscillates between potential and kinetic forms. In a resonant system it is possible to have a large accumulation of stored energy while the system has only weak excitation. Accumulation occurs when the rate of energy injection into the system is greater than the rate of energy loss from the system [6].

The behavior of an isolated resonator can be described by two fundamental parameters, its resonant frequency and its intrinsic loss rate Γ [7]. The ratio of these two parameters defines the resonator or quality factor (), a measure of how well it stores energy.

An example of an electromagnetic resonator is the circuit shown in the figure, which contains an inductor, a capacitor and a resistor.

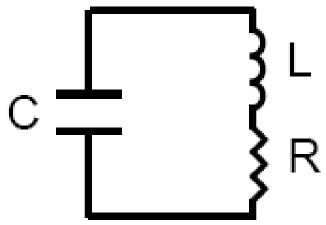


Figure 1: Electromagnetic Resonator

1.2 Concept of Wireless Power Transfer

The inductive coupling is the resonant coupling between the coils of two LC circuits with the same resonant frequency, transferring energy from one coil to the other coils [5].

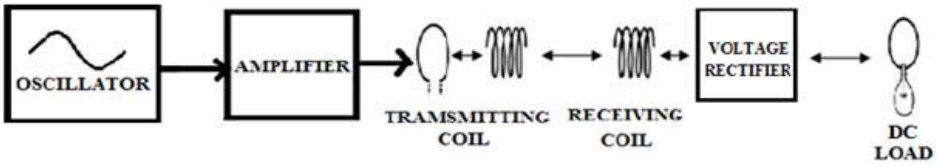


Figure 2: Wireless Power Transfer using Inductive Coupling

In inductive resonance, electromagnetic energy is only transmitted to receiving devices that have the same resonant frequencies as the power source, so energy transmission efficiency is maintained even in the event of misalignment [8].

II. PRACTICAL APPLICATION

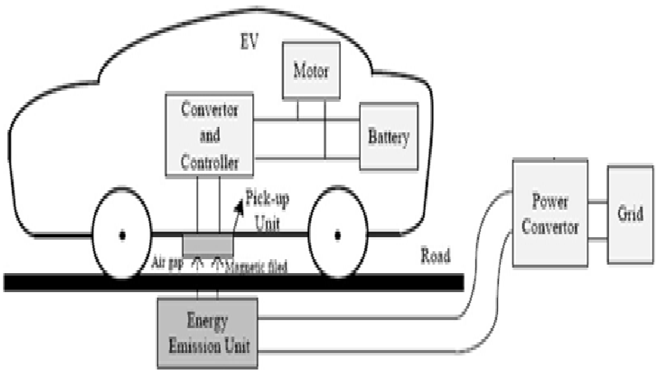


Figure 3: Practical Application

Electrical energy flows from the transmitter coil inside the platform to the receiver coil in the floor of the electric vehicle [9]. As soon as the resonant frequency of the two coils matches, the vehicle is charged electrically and automatically. When the vehicle is moved, the charger goes into power saving mode and turns off the charging coil.

2.1 Basic Design

A wireless power transmission system uses inductive coupling [10]. One of the most important factors to consider when designing an inductively coupled system is the target performance of the system. Voltage and current ranges, usable devices and operating frequency of the system depend on the target performance. Since the wireless power transmission system for moving electric vehicles is a utility system installed on a highway, the government needs to allow the use of the resonance frequency.

In general, wireless power transmission systems for electric vehicles use a frequency of 10 to 100 kHz. In the EV system, the target power is 100 kW and the resonance frequency is 78 kHz [11]. The circuit is basically the same as the circuit model of transformers. In the circuit, a large mutual inductance r M facilitates more efficient power transfer. The mutual inductance M is determined by L1, L2 and the coupling factor k as follows:

$$M = k\sqrt{L_1 L_2}$$

Here K value indicates degree of coupling strength which is between zero and one.

III. PROPOSED WIRELESS CHARGING METHODOLOGY

The proposed system demonstrates a wireless energy transfer design for EV dynamic charging applications. The dynamic wireless charging rail has a modular structure. Each module has two transmitter coils arranged together and connected to a single inverter to reduce the number of inverters. Receiver coil length has been optimized with two pickup coils used to reduce output power fluctuations. The inverter can operate over a wide frequency range to improve transmitter efficiency. And the dual-coil design of transmitter and receiver ensures optimal power flow and reduces jitter. With this system, the electric vehicle is charged via wireless charging on the go, so that the battery size can be reduced and there is no waiting time for charging. The main goal of our project is to design and develop an antenna and a wireless power transmission system suitable for electric vehicle (EV) moving. Using the principle of resonant magnetic coupling, a wireless power transmission technology to the electric vehicle is being developed. When the frequency of the vehicle's power receiver is precisely tuned to the resonant frequency of the transmitter unit under the road, electrical energy flows from the transmitter coil inside the platform to the receiver coil outside. This project describes the design and implementation of a wireless energy transfer system for moving electric vehicles involving the EV model system. The spacing between the transmitter coils is adjusted to reduce power pulsation.

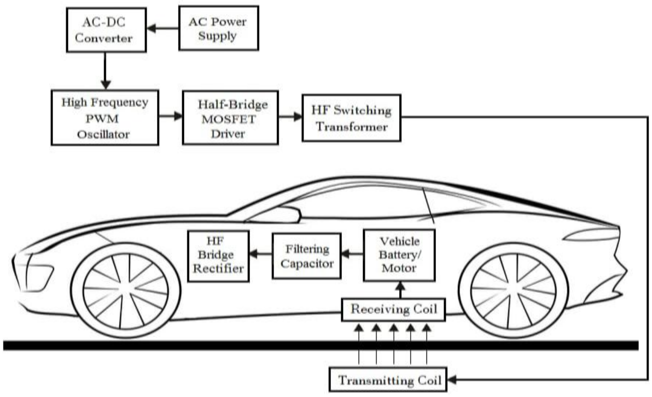


Figure 4: Proposed Hardware Block Diagram

3.1 Block Diagram Description

In the diagram, the left half is the transmit part of the circuit and the right half is the receive part of the circuit. In the middle is the equivalent circuit diagram of the transmitting and receiving coil, i.e. an inductive coupling. The transmit circuit is built with a high half-bridge inverter consisting of two N-channel MOSFETs.

The MOSFETs are driven by gate pulses generated by the PWM gate pulse block below the op amp based circuit. It generates two 65 kHz switching pulses with a duty cycle of 0.5. The two pulses are 90 degrees out of phase.

The transmitter circuit converts DC 12V to AC 12V at 65 kHz. The high-frequency alternating current is sent to the transmitter coil. The receiver coil receives energy through electromagnetic induction. The output of the receiver coil will also be 65 kHz high frequency AC. The AC voltage received is converted into DC voltage by the fast-switching bridge rectifier. Finally, a capacitor creates a stable DC output that can be used for charging.

3.1.1 Ac Power Supply

The wireless power transmitter is powered by an AC220v source.

3.1.2 AC-DC Adapter (SMPS)

The switching power supply is used here to convert alternating current into direct current. Here the input of the SMPS is 220V AC and the output is 12V DC.

3.1.3 High Frequency PWM Oscillator

The high frequency oscillator is designed with KA3525 IC. The IC circuit generates PWM switching pulses to drive the MOSFETs. The oscillator generates a PWM frequency of 65 KHz. Two separate PWM pulses PWM1 and PWM2 are generated here, which are fed to the two MOSFET gates. Each PWM pulse is 90 degrees out of phase, resulting in alternating switching of each MOSFETs.

3.1.4 Driver MOSFETs

Here two driver MOSFETs are used to switch the high frequency transformer. Both ends of the primary winding of the transformer are connected to the "drain" pin of the two MOSFETs. When one of the MOSFETs turns on, a current flow occurs in the primary winding of the transformer. Half of the primary winding is activated by one MOSFET and the other half by another MOSFET. The two MOSFETs switch alternately, creating an AC square wave in the primary winding of the transformer.

3.1.5 High Frequency Transformer

Here the DC-AC conversion takes place in the high-frequency switching transformer. In contrast to the normal transformer, the core of the HF transformer is made of ferrite, which makes it suitable for higher frequencies. Due to the high-frequency switching, the conversion losses are significantly lower than with a normal transformer. Here the high-frequency transformer converts direct current into high-frequency alternating current. The primary of the transformer has three bands; One is the center tap for the DC input and the other two are for the current return path through the MOSFETs during switching. The secondary output is RF AC power, which is delivered to the transmitter coil.

3.1.6 Half Bridge Inverter

The half-bridge inverter circuit driver consists of a high-frequency switching transformer and two MOSFETs. The primary switching transformer is connected to two MOSFETs and the secondary is connected to the driver coil. The half-bridge inverter converts the input DC voltage into a high-frequency AC voltage.

3.1.7 Transmitting Coil

The transmitting coil consists of copper coils that convert high frequency oscillating electric current into electromagnetic waves that oscillate at a specific frequency.

3.1.8 Receiving Coil

The receiving coil receives the electromagnetic waves from the transmitting antenna and converts them back into a high frequency electrical output.

3.1.9 HF Bridge Rectifier

The radio frequency (RF) rectifier bridge consists of fast-switching rectifier diodes that convert the RF AC voltage from the receiver coil to a DC voltage.

3.1.10 Filtering Capacitor

The filter capacitor filters the ripple generated in the rectifier and produces a smooth and stable DC output voltage that can be used to drive the vehicle engine or charge the battery.

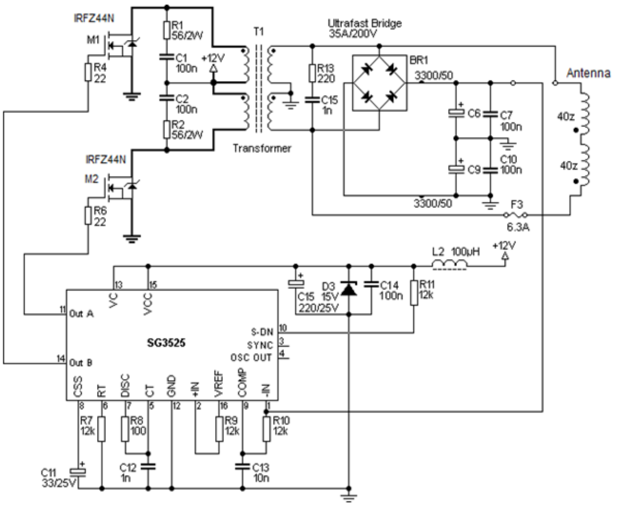


Figure 5: Transmitter Circuit diagram

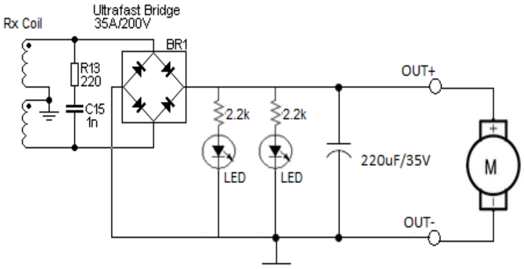


Figure 6: Receiver Circuit Diagram

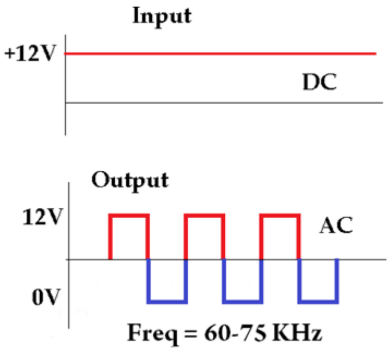


Figure 7: Input and Output of High Frequency Inverter

3.2 WPT Circuit Explanation

Here the transmitter is the first left half. For this, DC12V is given to the transmitter circuit. The transmitter circuit is essentially a high frequency inverter. DC current is switched by MOSFET and sent to the emitter coil through the center tap. The alternating switching of the MOSFETs creates a high-frequency alternating current in the transmitter coil. Then the coil generates an electromagnetic field.

The secondary side receives the electromagnetic field and converts it back into alternating current. It is then rectified via a diode bridge and a continuous output is obtained. A PWM oscillator IC is used for providing MOSFET gate pulses. The IC generates 65 kHz switching pulses. The comparator here acts as a square wave PWM pulse oscillator.

The primary inductance acts as a transmitter coil. The secondary inductance acts as a receiving coil. Here the energy flow is as follows,

- 12 VDC at 12 VAC (65 kHz) at the transmitter.
- 12 VAC (65 kHz) to 12 VDC in the receiver.

IV. CIRCUIT EXPLANATION

4.1 Transmitter section

The first circuit section is the high frequency inverter designed with SG3525 IC. Outputs a high-frequency PWM signal. The frequency range is 60 to 75 KHz.

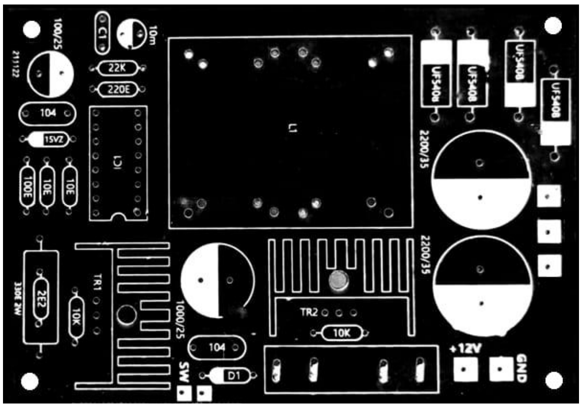


Figure 8: Transmitter Circuit PCB

The second part represents the half-bridge driver circuit made up of two N-channel MOSFETs. The MOSFET drivers pass the PWM signal to the primary side of an RF switching transformer.

The third section is the high frequency transformer. It converts the DC input fed into the primary coil by the MOSFETs into an RF AC output on its secondary coil.

The fourth section is the transmitter coil. It converts the supplied HF alternating current into electromagnetic waves. The SG3525 IC is basically a PWM oscillator chip that outputs a high frequency PWM signal that can directly drive MOSFETs to turn them on and off. The frequency of the PWM signal can be tuned and also adjusted using the timing control resistor and capacitor connected to pins 6 and 5 (RT and CT). The IC has two PWM outputs which are pins 11 and 14 (Output A and Output B). Two PWM outputs are connected to the gates of MOSFETs connected in a half-bridge configuration. The transmitter coil is a coil with a center tap, so it has three connections. The drains of the two MOSFETs are connected to both ends of the emitter coil. The center tap of the coil is connected to the DC supply which is 12V.

When switched on, the SG3525 IC starts to oscillate and outputs PWM signals. MOSFETs connected to its outputs turn on and off alternately. The A output and B output of the IC output are 90 degrees out of phase. So when one MOSFET is on, the other is off. Here we use an oscillator frequency of 60-80 KHz. Thus, MOSFETs are switched at high frequency. When the MOSFET is on, DC current flows from the center tap of the emitter coil, through the drain of the MOSFET and into the source, which is connected to ground. In the first half-wave, the direct current direction is therefore in the first half of the transmitter coil. Likewise, the current flow for the next half cycle will be in the second half of the coil. Therefore, the two MOSFETs generate a current flow that goes in the opposite direction on each switching cycle. This creates an alternating current in the transmitter coil. This configuration thus generates a high-frequency alternating current from the input direct current. The transmitter coil converts the HFAC electrical current into an HF electromagnetic field. The transmitter coil absorbs the electric current and transmits it in the form of electromagnetic waves.

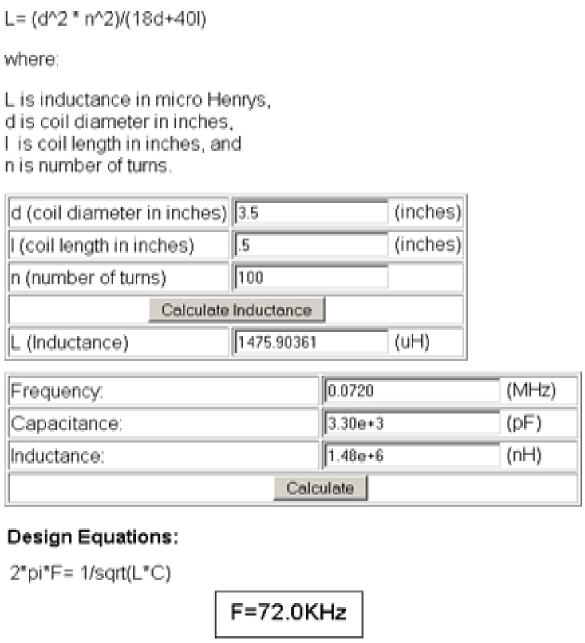
4.2 Receiver Section

Receiver has a three section.

1) First is the receiver coil
2) Second is the High-Frequency rectifier
3) Third is the DC ripple filter

The receiver has a receiving coil that has the same resonant frequency as the transmitting coil. It picks up the electromagnetic field near the transmitter coil and converts it into high-frequency alternating current. The output of the receiver coil is fed to a high frequency rectifier that converts the RF AC output to DC. A filter capacitor at the output of the rectifier filters the DC ripple and ensures a stable DC output voltage. A DC output is generated at the receiver output, which is used to power any DC load.

V. FREQUENCY CALCULATION OF TRANSMITTER & RECEIVER COILS



L= (d^2 * n^2)/(18d+40l)

where:

L is inductance in micro Henrys,
d is coil diameter in inches,
l is coil length in inches, and
n is number of turns.

d (coil diameter in inches)	3.5	(inches)
l (coil length in inches)	.5	(inches)
n (number of turns)	100	
L (Inductance)	1475.90361	(uH)

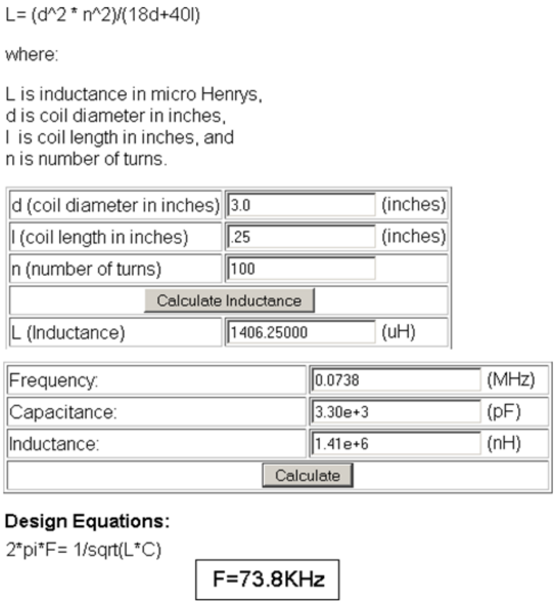
Frequency:	0.0720	(MHz)
Capacitance:	3.30e+3	(pF)
Inductance:	1.48e+6	(nH)

Design Equations:

2*pi*F= 1/sqrt(L*C)

F=72.0KHz

Figure 9: Frequency Calculation of Transmitter Coil



L= (d^2 * n^2)/(18d+40l)

where:

L is inductance in micro Henrys,
d is coil diameter in inches,
l is coil length in inches, and
n is number of turns.

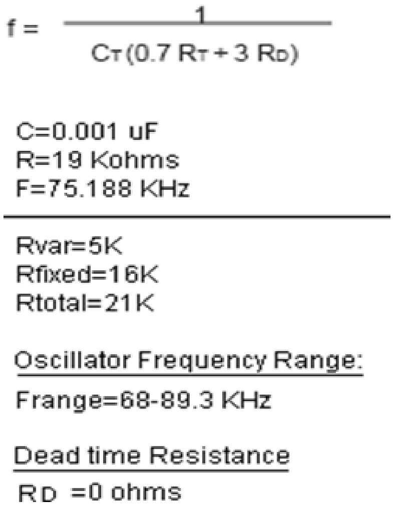
d (coil diameter in inches)	3.0	(inches)
l (coil length in inches)	.25	(inches)
n (number of turns)	100	
Calculate Inductance		
L (Inductance)	1406.25000	(uH)

Frequency:	0.0738	(MHz)
Capacitance:	3.30e+3	(pF)
Inductance:	1.41e+6	(nH)
Calculate		

Design Equations:
2*pi*F= 1/sqrt(L*C)

F=73.8KHz

Figure 10: Frequency Calculation of Receiver Coil



$$f = \frac{1}{C_T(0.7\,R_T + 3\,R_D)}$$

C=0.001 uF
R=19 Kohms
F=75.188 KHz

Rvar=5K
Rfixed=16K
Rtotal=21K

Oscillator Frequency Range:
Frange=68-89.3 KHz

Dead time Resistance
R_D =0 ohms

Figure 11: PWM Frequency Calculation of KA3525

VI. RESULT AND DISCUSSION

Table 1: Observed Power, Efficiency vs Air gap between Transmitter and Receiver Coils

Power in (W) 12V, 0.5A	Power Out (W)	Efficiency	Air gap (cm)
6	5.1	85	1
6	5.1	85	1.5
6	5.0	84	2
6	4.92	82	2.5
6	4.68	78	3
6	4.2	70	3.5
6	2.4	40	4
6	1.0	18	4.5
6	0.48	8	5

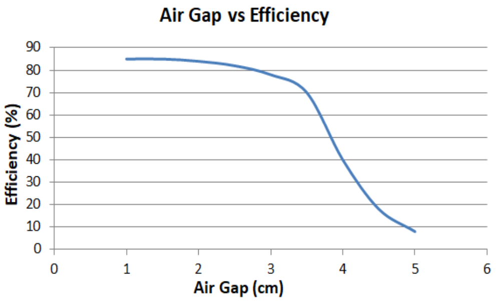


Figure 12: Air Gap vs Efficiency

System settings affect the coupling coefficient; Lm is the mutual inductance parameter, while L1 and L2 are non-linear loss resistance values that depend on the frequency and the characteristic impedance of the system. The validation of results is done using finite element method. The vertical distance from the power transfer efficiency curve is shown in the figure. With increasing vertical distance, the leakage flux increases and the magnetic flux within the secondary-side core decreases.

About 80% of the maximum efficiency can be achieved when the vertical distance is 2cm as shown in the figure. The efficiency decreases essentially linearly because the decrease in flux linkage in the secondary coil is caused simply by increasing the vertical distance. We conclude that equivalent circuit analysis by numerical calculation is suitable for determining voltage and current waveforms. Furthermore, the transmission efficiency in a different distance range can be calculated based on the electric ratio.

The efficiency results with regard to load changes show that there are areas with a double resonance frequency as well as areas with a single resonance.

Depending upon the length of the air gap, the resonant frequency tends to change from two points to one point. The double resonance frequency range occurs at low impedance and short range. As the gap spacing and impedance increase, a region of resonance appears. In this operating range, the efficiency drops sharply.

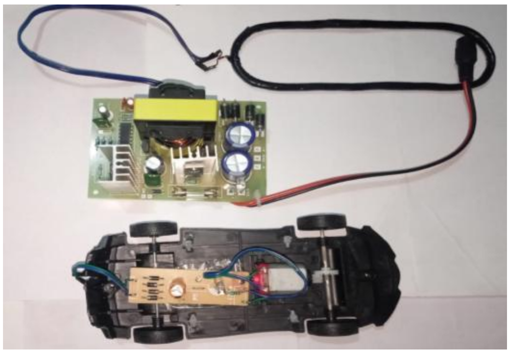


Figure 13: Prototype of Hardware

VII. CONCLUSION

In this project we have designed and implemented a hardware prototype of dual coil based wireless charging system for EVs. Design is applicable practically for both static and dynamic charging systems. Magnetic coupling between transmitter and receiver coils is made efficient by using double coil design. The charging coils in the lane are designed for modularly so that they can be arranged as separate modules without any interlinking problem. Dual pick-up coil in the vehicle reduces the fluctuations in the output power of the receiver. The high frequency inverter is designed to operate over a wide frequency range which make is it versatile to withstand any frequency deviations. Overall system is designed to operate at its maximum efficiency in all practical conditions.

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Citation of this Article:

Sahil Ansari, Shivam Kumar Rai, Shiv Kumar Verma, “Dynamic Wireless Charging System for Electrical Vehicles” Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 7, Issue 4, pp 149-155, April 2023. Article DOI https://doi.org/10.47001/IRJIET/2023.704024

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